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Compact, Continuous-Beam, Cold-Atom Clock for Satellite Applications

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14. ABSTRACT

Highly stable atomic frequency standards are of increasing importance for a variety of space applications, ranging from communication to navigation and time transfer to tests of fundamental science. The requirements for an atomic clock vary significantly depending on the application, and for many space systems, compactness and robust design are at a premium, and stability dominates over absolute accuracy. We report on progress with our design for a compact laser-cooled Cs-beam atomic clock suitable for satellite applications such as GPS. The basic design features a continuous, cold atomic beam extracted from a magneto-optic trap (MOT). This cold atomic beam is then to be used in a laser-pumped Ramsey clock, with the clock signal derived from either a microwave C-field or, alternatively, by Raman resonance between the Ramsey fields. In order to reduce light shifts from the MOT light and improve signal-to-noise, the atomic beam will be optically deflected and transversely cooled upon extraction from the MOT. We estimate that the shot-noise-limited stability achievable with this physics package can be 2 to 3 orders of magnitude better than current Cs-beam clocks used in satellite applications. We present our experimental progress towards a working frequency standard, including characterization of our six-beam magneto-optic cold atom trap and production and characterization of a cold atomic beam.

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A COMPACT, CONTINUOUS BEAM COLD ATOM CLOCK FOR SATELLITE APPLICATIONS

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Abstract

Highly stable atomic frequency standards are of increasing importance for a variety of space applications, ranging from communication to navigation and time transfer to tests of fundamental science. The requirements for an atomic clock vary significantly depending on the application, and for many space systems compactness and robust design are at a premium, and stability dominates over absolute accuracy. We report on progress with our design for a compact laser-cooled Cs-beam atomic clock suitable for satellite applications such as GPS. The basic design features a continuous cold atomic beam extracted from a magneto-optic trap (MOT). This cold atomic beam is then to be used in a laser-pumped Ramsey clock, with the clock signal derived from either a microwave C-field or alternatively by Raman resonance between the Ramsey fields. In order to reduce light shifts from the MOT light and improve signal-to-noise, the atomic beam will be optically deflected and transversely cooled upon extraction from the MOT. We estimate that the shot-noise-limited stability achievable with this physics package can be two to three orders of magnitude better than current cesium-beam clocks used in satellite applications. We present our experimental progress towards a working frequency standard, including characterization of our six-beam magneto-optic cold atom trap and production and characterization of a cold atomic beam.

INTRODUCTION

Laser cooling and trapping technology prepares atomic samples at a thermal temperature of well below 1 mK without using cryogenic techniques. At such ultra-low temperatures, Doppler effects associated with thermal atomic gases can be ignored, and other noise sources originating from the thermal motion of atoms are tremendously reduced. In the last decade, state-of-the-art laser cooling and atom-trapping techniques have led to revolutionary advances in precision measurement, in particular the development of a new generation of highly stable atomic clocks/frequency standards [1,2]. Today the most precise time and frequency references, with uncertainties at the level of 10^{-15}, are provided by laser-cooled atomic fountain frequency standards, developed and maintained in a number of national metrology laboratories around the world [3]. Due to the high demand for better time/frequency-keeping devices for applications such as deep space navigation, experiments aboard the International Space Station, satellite communication, and satellite global positioning (GPS), efforts aimed at developing space-qualified atomic clocks using laser-cooled atoms have recently been under way in national and university laboratories [4]. Because of the special environment in space, the tasks to develop laser-cooled atomic clocks to fly on-board satellites face many new challenges. Since the well-developed atomic fountain cannot be used under microgravity conditions, new technical approaches need to be explored. The requirements for small sizes, light weight,

compact system design, radiation resistance, and hardware reliability are also essential to qualify an atomic clock physics package for space applications.

At The Aerospace Corporation, efforts to apply laser cooling and trapping technology to develop a cold cesium (Cs) beam atomic clock suitable for satellite applications started about 3 years ago [5,6]. Under microgravity conditions in space the atom-microwave interaction time is no longer influenced by gravity as in the case of an atomic fountain on the ground. The main idea of our effort is to replace the thermal oven in a conventional Cs-beam atomic clock with an ultralow-temperature atomic source, a laser-cooled atom trap that can generate an ensemble of 10^7–10^8 cold Cs atoms at a thermal temperature T < 1 mK. The cold Cs atoms are then extracted from the atom trap to form an atomic beam. Since the atomic beam starts from atoms almost at rest (the atomic thermal velocity in the atom trap is as low as 20 cm/s), a very low beam velocity of ~10 m/s is achievable [7]. In this way, we can dramatically increase the clock interrogation time with a relatively short Ramsey microwave cavity. For example, if the Ramsey cavity has a length of 20 cm, a beam of Cs atoms traveling at a speed of 10 m/s has a transient interaction time of 0.02 s, resulting in a Ramsey fringe width about 33 Hz [8]. For comparison, if a conventional thermal atomic beam with a velocity of 100 m/s is used, a Ramsey interaction cavity of 2 m long is required to generate the same line-width. In addition to the use of laser-cooled atomic samples, laser optical pumping and laser-induced fluorescence will be used for preparing and detecting, respectively, the clock states with a nearly 100% efficiency.

VAPOR-CELL MAGNETO-OPTICAL TRAP (MOT)

Magneto-optical trapping of neutral atoms [9] is now the most commonly used technique for cold atom-related experiments and applications. As shown schematically in Figure 1, a vapor-cell MOT is composed of three main components: (1) three pairs of mutually orthogonal, circularly polarized laser beams that trap and cool the Cs atoms three dimensionally; (2) a pair of anti-Helmholtz coils generating an inhomogeneous magnetic field that defines the position of the trap; and (3) an ultra-high-vacuum chamber filled with Cs atomic vapor dispensed from a Cs metal reservoir. In the case of Cs shown in Figure 1, the atomic transition responsible for the cooling and trapping effects is the $6^2S_{1/2}(F'' = 4) \rightarrow 6^2P_{3/2}(F' = 5)$ transition. A second laser frequency is set on resonance for the $6^2S_{1/2}(F'' = 3) \rightarrow 6^2P_{3/2}(F' = 4)$ transition to optically re-pump the atoms back to the upper $F'' = 4$ hyperfine level. The cold-atom trap is loaded from the room-temperature Cs vapor by capturing Cs atoms with low velocities in the Maxwell-Boltzmann thermal distribution. The atoms are cooled in a three-dimensional optical molasses [1,9] formed by the six trapping laser beams to well below 1 mK. The loading process of a vapor-cell MOT can be described by a rate equation:

$$dN(t)/dt = R - \gamma N(t), \qquad (1)$$

where $N(t)$ is the number of atoms captured at time t, R the trap loading rate, and γ the total trap loss coefficient. When the trap is fully loaded, a steady-state ($dN/dt = 0$) is approached with $N_s = R/\gamma$, where N_S is the number of trapped atoms. With $N(T = 0) = 0$, an exponential solution to Eq. (1) can be obtained:

$$N(t) = N_s(1 - e^{-t/\tau}), \qquad (2)$$

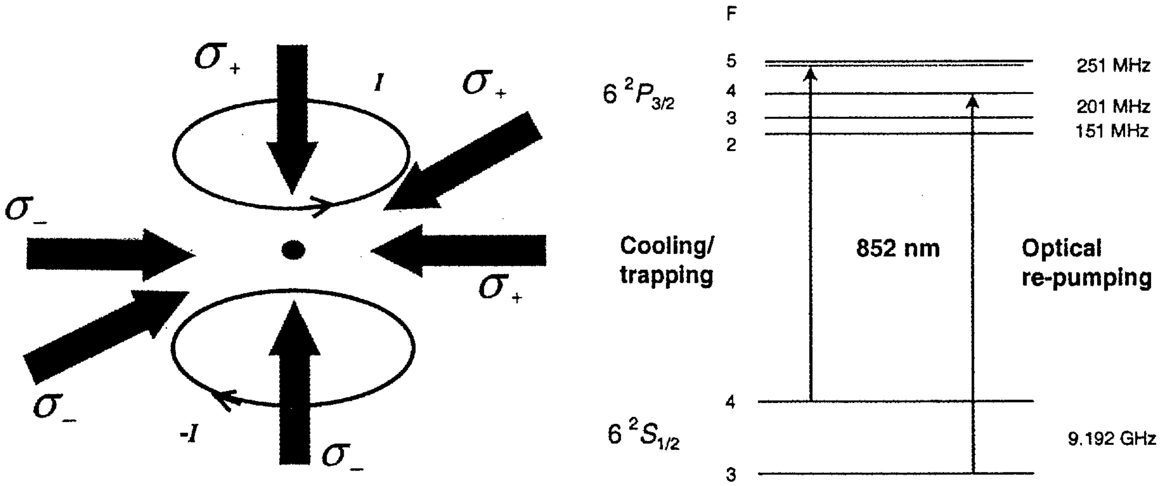


Figure 1. Schematic diagram of a magneto-optical trap (MOT) and relevant hyperfine structure energy levels of Cs atoms. The cooling/trapping laser frequency is set slightly below the $6^2P_{3/2}$ ($F' = 5$) hyperfine level, and the optical re-pumping laser is tuned on resonance between $6^2S_{1/2}$ ($F'' = 3$) and $6^2P_{3/2}$ ($F' = 4$) levels, as discussed in the text. The σ_+ and σ_- stand for $\Delta m = \pm 1$ transitions induced by circularly polarized laser beams. I is the electrical current flowing through the coils.

where $\tau = 1/\gamma$ is the 1/e trap loading time constant. The total trap loss coefficient γ in Eq. (1) is attributed to two collision processes: (1) collisions of trapped cold Cs atoms with background residual gases of the vacuum chamber, and (2) collisions of trapped cold Cs atoms with hot Cs atoms in the Cs atomic vapor. The trap loss rates of the two mechanisms are proportional to the number of atoms in the trap. Note that the trap loss induced by collisions between trapped cold Cs atoms is ignored in Eq. (1) because cold collisions are important only at very high trap density, which our system is not designed to reach. The trap loading rate, which determines the flux of the atomic beam to be formed from the MOT, is $R = N_s\gamma = N_s/\tau$, and thus can be determined by measuring the total number of trapped atoms N_s and the trap loading time constant, τ. After a brief description of the apparatus, the remainder of this paper will describe our measurements and optimization of these MOT parameters and the implications for cold atom clock performance.

LABORATORY TESTBED FOR CS MOT

Figure 2 shows a simplified diagram of the Cs magneto-optical trap (MOT). The trapping and optical re-pumping laser beams are provided by two 150 mW distributed-Bragg-Reflection (DBR) diode lasers (SDL 5722)*. These single-mode DBR lasers has a short-time effective linewidth of ~3 MHz, and the laser frequency is actively stabilized using a saturated absorption spectrometer for long-term frequency stability. Specifically, the trapping laser is locked to the crossover saturated absorption line (125 MHz below the highest $F' = 5$ level) between the transitions, $6^2S_{1/2}(F'' = 4) \rightarrow 6^2P_{3/2}(F' = 5)$ and $6^2S_{1/2}(F'' = 4) \rightarrow 6^2P_{3/2}(F' = 4)$. The optical re-pumping laser is stabilized to the $6^2S_{1/2}(F'' = 3) \rightarrow 6^2P_{3/2}(F' = 4)$ transition. The trapping laser frequency, after being up-shifted by 100 MHz using an acousto-optical modulator (IntraAction ATM-1001A2), is 25 MHz red-detuned from the $6^2P_{3/2}(F' = 5)$ hyperfine level. This red detuning is adjustable by tuning the rf frequency of the AOM driver (IntraAction VFE-1102A4). The inhomogeneous magnetic field is created by anti-Helmholtz coils placed outside the ultrahigh vacuum chamber.

* These components are no longer available from the manufacturer.

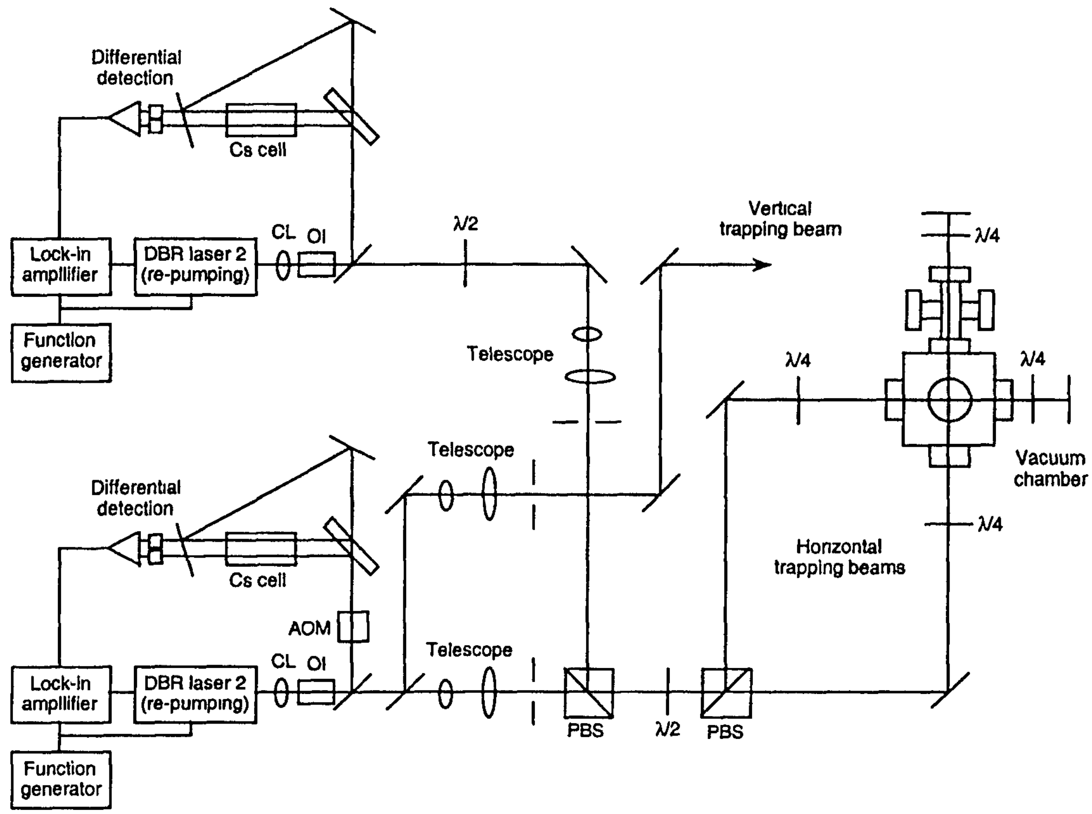


Figure 2. Simplified schematic diagram of the Cs magneto-optical trap testbed. The vacuum chamber has a background pressure < 1×10^{-9} Torr and contains Cs atomic vapor at a controlled pressure. Two frequency-stabilized diode lasers provide the cooling/trapping and optical re-pumping beams. AOM: acousto-optical modulator, CL: collimation lens, OI: optical isolator, PBS: polarization beam splitter, λ/2: half-wave waveplate and λ/4: quarter-wave waveplate. A third diode laser (not pictured) is used to provide laser-induced fluorescence for the time-of-flight measurements of the cold atomic beam.

CHARACTERIZATION OF CS MOT PERFORMANCE

Figure 3 shows an enlarged fluorescence image of the trapped Cs atomic cloud. The prolate ellipsoidal shape is due to the shape of the inhomogeneous magnetic field of the anti-Helmholtz coils. The spatial scale of the CCD camera is calibrated to be 8.2 pixels/mm under our experimental conditions. From this image we measure the MOT dimensions (FWHM) to be 1.3 mm × 0.9 mm, giving a trap volume of ~1 mm^3.

The main purpose of the Cs magneto-optical trap developed here is to generate a cold Cs atomic beam. We therefore optimize the trap parameters to maximize the total number of trapped atoms. Figure 4 presents the trap fluorescence intensity as a function of the axial magnetic field gradient when the trapping laser-beam diameter is 15 mm and the laser detuning is –25 MHz. We found that the trap captures more atoms with dB/dz = 16 – 18 gauss/cm. The error bars are smaller at higher field gradient because the trap becomes tighter and denser.

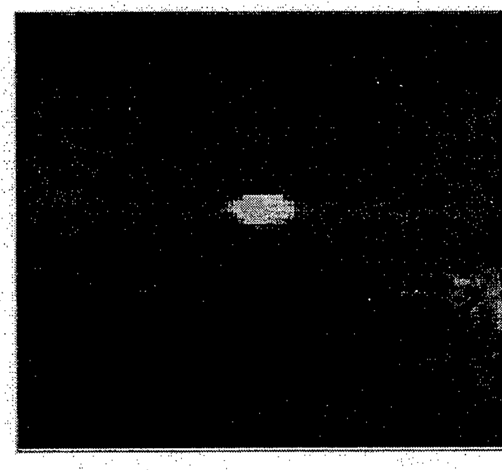


Figure 3. Trapped Cs atomic cloud fluorescence recorded by a CCD camera system. This image is digitized and measured to determine trap dimensions.

The trap-loading curve is recorded with a photomultiplier tube and a digital oscilloscope. An electronically controlled mechanical shutter is used to turn on and off all the trapping laser beams. We fit the experimental data to Eq. (2) and determined the 1/e trap loading time constant τ = 0.42 s under our experimental conditions. We can obtain an estimate of the thermal temperature of the trapped atoms by the method of release and recapture. This method measures the thermal velocity of the cold atoms by suddenly releasing the trap at $t = 0$ and restoring the trap to recapture the escaping atoms at $t = \Delta t$ where Δt is the release time. The overlapping region of the six laser beams with diameter d_{laser} defines a volume approximately having a diameter of d_{laser}. This volume is called the recapture volume, in which atoms just released from the trap can be recaptured quickly within a few milliseconds. If the released atoms travel fast enough to leave the recapture volume during the release time Δt, the trap has to be reloaded with a normal loading process, which has a time constant of ~0.5 s. By measuring the difference in trap fluorescence intensity before the release of the trap and immediately after the trapping beams are turned back on, we obtain the ratio of atoms being recaptured as a function of the release time, Δt, as shown in Figure 5. The trap release and recapture process is simulated based on a Maxwell-Boltzmann velocity distribution at a thermal temperature T and with a laser-beam diameter of 15 mm. The best fit to the measured recapture ratio gives an estimation of the trap temperature of ~300 μK. Also shown in Figure 5 are the calculated recapture ratios at T = 200 and 500 μK.

We determine the total number of trapped atoms, n_{trap} by comparing the trap fluorescence intensity with the fluorescence intensity of the surrounding Cs vapor, both induced by the trapping laser beams. We image the trap cloud onto a CCD camera from a distance of 35 cm with a f = 2.5 cm lens. The video signal intensity is approximately proportional to the linear integration of the number density of the atoms that emit light [10]. It can be shown that the number of trapped atoms is related to the measured fluorescence intensities by

$$n_{trap} = \left(\frac{S_{trap}}{S_{vapor}}\right)\left(\frac{d_{laser}}{d_{trap}}\right) n_{vapor}, \qquad (3)$$

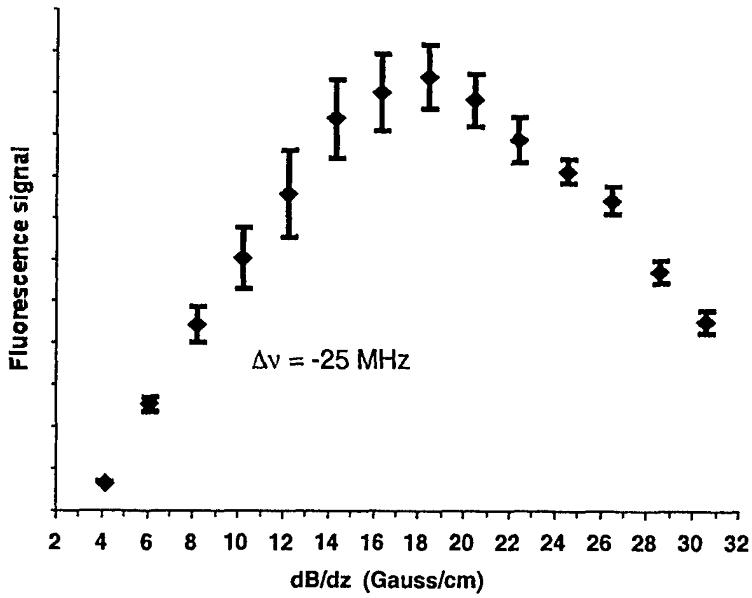


Figure 4. Atomic fluorescence intensity as a function of the axial magnetic field gradient. The fluorescence intensity is proportional to the total number of Cs atoms in the MOT.

where $S_{trap(laser)}$ is the measured fluorescence signal for the trapped cloud (background vapor). We measured the trap image intensity to be 150 times more intense than that of the Cs vapor, *i.e.* $S_{trap}/S_{vapor} = 150$. Given the trap diameter $d_{trap} \approx 1$ mm from Figure 3, and the laser-beam diameter $d_{laser} = 15$ mm, we have $d_{laser}/d_{trap} = 15$.

An important difference between the trapped cold atoms and the surrounding room-temperature Cs vapor is the line-broadening mechanism. For the trapped Cs atoms at 300 μK, the inhomogeneous Doppler broadening can be ignored, and the homogeneous natural linewidth is 5.18 MHz. For the surrounding Cs atomic vapor at the lab temperature (296 K), however, the Doppler broadening is dominant and has a linewidth of 376 MHz. Therefore, the narrow-band laser beam interacts only with the velocity group of Cs atoms in the vapor whose Doppler-shifted transition frequencies are in resonance with the laser frequency. By taking into account the homogeneous power broadening induced by the trapping laser beam (~17 MHz) and the laser frequency offset ($\Delta\nu = -25$ MHz), we find that only about 7% of the atoms in the Cs vapor contribute to the fluorescence intensity. In addition, the optical transition for atoms in the Cs vapor is saturated by the laser beams at a saturation factor $S_{0\,vapor} \approx 10$, while the cold atoms in the trap are saturated only at $S_{0\,trap} = 4$, given that the laser frequency is offset by 25 MHz ($\approx 5\gamma$) to the red. Therefore, the ratio $S_{0\,vapor}/S_{0\,trap} = 2.5$. Using Eq. (3) and all the factors discussed above, we have:

$$n_{trap} = 150 \times 15 \times 0.07 \times 2.5 \times n_{vapor}. \tag{4}$$

The number density of the Cs vapor in the center region of the vacuum chamber is estimated to be $(2 \pm 1.3) \times 10^{8}$ cm^{-3}, resulting in a trap density:

$$n_{trap} = (8 \pm 5) \times 10^{10}\ \text{cm}^{-3}. \tag{5}$$

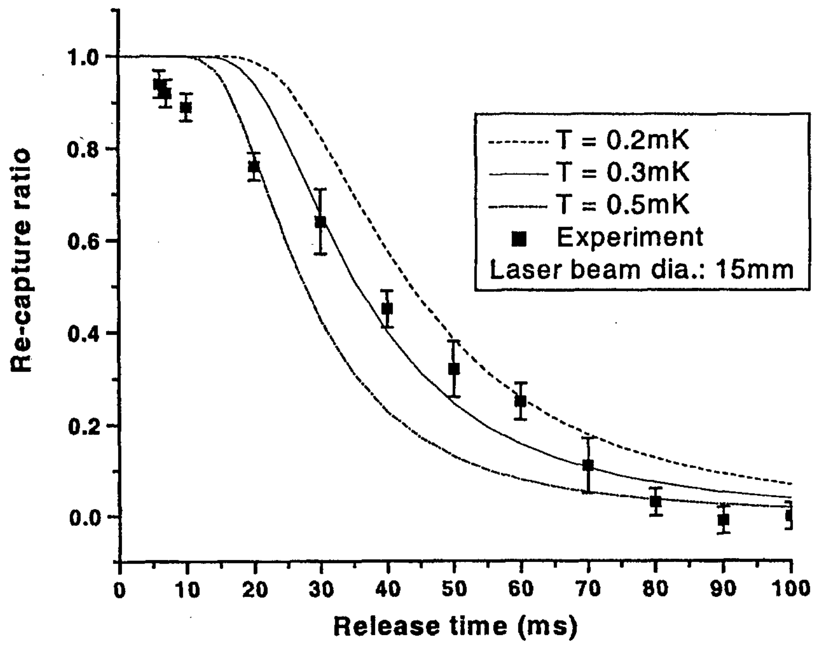


Figure 5. Trap temperature measurement by release and recapture method. Computer simulation of the release and recapture process and comparison with the experimental data indicate that the Cs magneto-optical trap has a thermal temperature of ~300 μK.

Given the trap volume $V_{trap} \approx 1\ \text{mm}^3$, the total number of trapped atoms is

$$N_{trap} = n_{trap} \times V_{trap} = (8 \pm 5) \times 10^7 \text{ atoms.} \qquad (6)$$

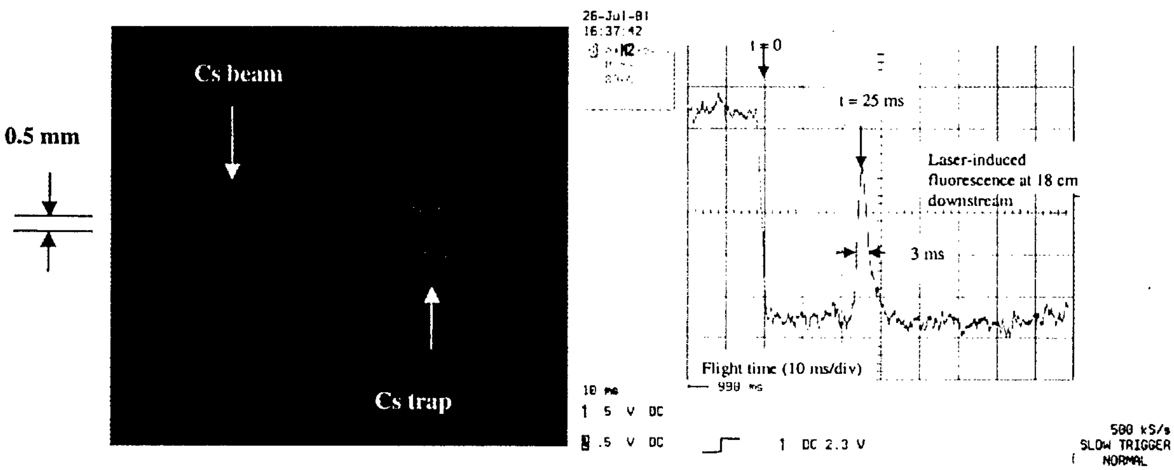
Table 1 summarizes the trap parameters discussed in this section.

Table 1. Summary of Measured Cs Magneto-Optical Trap Parameters

MOT parameter	Measured value
Red-detuning ($\Delta\nu$)	-25 MHz ($\approx$ -5γ)
Magnetic field gradient (*dB/dz*)	16 Gauss/cm
Laser beam diameter	15 mm
Total number of trapped atoms	$(8 \pm 5) \times 10^7$ atoms
Trap volume	~ 1 mm^3
Atomic density	$(8 \pm 5) \times 10^{10}$ atoms/cm^3
Trap temperature	300 (200 < T < 500) μK
Trap loading time constant	0.4 s

PRODUCTION OF SLOW, COLD ATOMIC BEAM

Having formed and characterized the MOT, we introduced a small opaque disk in one of the six MOT beams, forming a dark column along the beam. In this configuration [7], atoms are captured and cooled until they enter the dark column shadow region, at which point they experience a pushing force from one direction with no restoring force along the dark column. (Cooling in the transverse dimensions remains.) The atoms are forced out of the MOT, forming a low-velocity atomic beam. A fluorescence image of the extracted beam is shown in Figure 6a. We have measured the velocity profile of the atomic beam by time of flight, as is shown in Figure 6b. The mean velocity is measured to be 7 m/s and the FWHM is about 1 m/s. The width is dominated by the spatial extent of the MOT: atoms from further back in the cloud are accelerated over a longer distance and reach a higher velocity. In the beam-formation configuration, the re-pumping laser is used only in the transverse beam pairs. After the atoms in the cold beam leave the re-pumping region, they eventually accumulate in the lower $F'' = 3$ level and are no longer accelerated. We have not yet performed quantitative measurements of the beam flux, but based on our measured MOT parameters expect the flux to be on the order of 2×10^8 atoms/s.



(a) (b)

Figure 6. (a) Enlarged fluorescence image.of cold atomic beam formation from MOT. (b) Time-of-flight measurement of beam velocity profile. The mean velocity is measured to be 7 m/s and the FWHM is about 1 m/s.

PROSPECTS FOR A COLD CS-BEAM ATOMIC CLOCK

In this section, we estimate the atomic clock parameters based on the actual Cs MOT performance and compare them with initial estimates made in References [5,6]. Table 2 summarizes the estimation made using the MOT parameters in Table 1 and the assumptions briefly described below.

First, we assume that almost all the trapped atoms can be extracted into the atomic beam as observed in Reference [7]. From the discussions in Section 2, the beam flux F then can be approximated as $F \approx R = N_S/\tau$, where R is the trap loading rate, N_S the number of trapped atoms, and τ the trap loading time constant. This means that the system works like a cold-atom funnel, *i.e.*, atoms are continuously captured

and cooled by the laser beams and then flow out forming an atomic beam. For an atomic beam clock, the signal-to-noise ratio is limited predominantly by atomic shot noise and can be estimated from the Cs-beam flux. We assume that a Ramsey microwave cavity with interaction length of 20 cm is used. Then a cold Cs atomic beam traveling at 7 m/s can generate Ramsey fringes with a width $\Delta\nu = 0.65/T_{trans}$ [8], where T_{trans} is the transient time the Cs atoms spend to pass through the cavity. In the estimation, the loss of atoms from the traveling beam is ignored. Finally, the Allen deviation [8,11] is estimated to be $(2.1 \pm 0.7) \times 10^{-13}\ \tau^{-1/2}$, which is in line with our initial estimates. These estimates are based on the atomic beam extracted from the MOT optimized as described above. Since, when the atomic beam is being formed, the dominant trap loss mechanism is transfer of atoms to the beam rather than collisions, we expect even higher beam fluxes to be possible with increased Cs vapor pressure.

In this paper we have concentrated on our results with a cold atomic beam extracted from a conventional six-beam MOT. Our long-term plans are based on a design [5,6] employing a single laser beam MOT [12] using a conical or pyramidal retroreflecting mirror with a hole at the apex. We expect similar slow, cold, high flux atomic beams to be realizable with this or other simpler designs that are attractive for satellite applications. In all designs, it is important to eliminate light from the MOT region that would contribute unacceptable light shifts to the clock signal. Current plans [5,6] are to deflect the cold-atom beam using an offset transverse laser-cooling region or deflecting magnets to separate the atomic beam from the laser light, and add additional light baffles to further reduce stray light.

Table 2. Expected Parameters of the Cold Cs Beam Atomic Clock Estimated According to the Cs MOT Parameters. Also listed are the proposed clock parameters from our earlier estimates [5,6].

Clock parameters	Expected atomic clock parameters based on MOT performance	Proposed atomic clock parameters [5,6]
Beam flux (F)	$(2 \pm 1.2) \times 10^8$ atoms/s	10^8 atoms/s
Beam velocity (v)	7 m/s	~10 m/s
S/N ratio	$(1.4 \pm 0.4) \times 10^4$	10^4
Clock interaction length (L)	20 cm	20 cm
Clock line width ($\Delta\nu$)	23 Hz	50 Hz
Clock frequency (ν_0)	9.192 GHz	9.192 GHz
Q factor ($\nu_0/\Delta\nu$)	4×10^8	1.8×10^8
Short-term stability $\sigma_y(\tau)$	$(2.1 \pm 0.7) \times 10^{-13}\ \tau^{-1/2}$	$1.1 \times 10^{-13}\ \tau^{-1/2}$

CONCLUSIONS

We have successfully constructed, demonstrated, and characterized a magneto-optical trap (MOT), which confines an ensemble of Cs atoms at a thermal temperature of ~300 μK and an atomic density of ~ 8×10^{10} cm^{-3}. This ultralow-temperature atom source serves as a source of a continuous laser-cooled Cs atomic beam with a velocity of 7 m/s ± 1 m/s. Based on our measured MOT parameters, we expect the beam flux

to be about 2×10^8 atoms/s; we expect higher fluxes to be realizable with further optimization. The measured Cs MOT parameters are in line with our initially proposed clock specifications, which lead to a hundred-fold improvement in stability over existing space-qualified atomic clocks.

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Questions and Answers

MICHAEL GARVEY (Datum TT&M): This is going to sound a little retro, but you have a fairly slow velocity coming out of the orifice and a fairly narrow velocity of distribution. Did you look at the possibility of using conventional magnetic deflection and state selection just to – ?

WALTER BUELL: That is a definite fallback position from the laser optical bumping, especially in the event that the various deflection and baffling techniques aren't able to sufficiently reduce the light shifts.

GARVEY: Magnets are a lot simpler than lasers.

BUELL: But if we are going to do the laser cooling, you have the lasers already.

ROBERT LUTWAK (Datum): I am actually going to follow up on Mike's question, which is to ask whether you have estimated the light shift from that steering standing wave configuration.

BUELL: No, we haven't yet. One of the reasons for that is that, one, we do not have optical designs of what the baffles are going to be and what the distances are going to be. And I am also playing with some other optical pumping techniques that would be based on dark states so that we can do the optical pumping and beam deflection all in the same region. And so there is still a lot of uncertainty as to what exactly is going happen in that region.

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